European Journal of Agronomy 100 (2018) 163–176

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Modelling crops and cropping systems—Evolving purpose, practice and prospects

Brian A. Keating, Peter J. Thorburn*

CSIRO Agriculture and Food, 306 Carmody Rd, St Lucia, Queensland 4067, Australia

ARTICLE INFO

Keywords:
Agricultural systems
Big data
History
Knowledge products
Next generation
Simulation

ABSTRACT

Crops and cropping systems are characterised by complexity and variability. Complexity arises from inherently complex plant and soil processes combined in an almost infinite set of permutations and combinations associated with biotic and abiotic drivers that are inherently variable in both space and time. Modelling has evolved over the last 100 years as a means of describing and interpreting complex and variable performance and increasingly as a means of predicting likely performance in prescribed circumstances for better decision making. In this paper we reflect on the evolution of quantitative approaches to describing and predicting crop growth and cropping system performance. We begin with early mathematical descriptions of plant and crop growth and soil processes dating from the 1920′s to 1950′s. We explore the early crop models of the 60′s and 70′s and the more comprehensive crop-soil models of the 1970′s and 80′s. Cropping systems models with comprehensive systems management capabilities underpinned by a modular design began to gain currency in the 1990s. Over this long period, the ambitions held by model-makers' for model applications grew. We analysed the publication records of major cropping systems models to summarise the broad trends in model applications that emerged in the early 21st Century, based on the 60 years of development in the 20th Century. There was an "explosion" in publications on cropping systems models, with an eight fold increase from 2000 to 2015. In parallel, the application of models greatly expanded from approximately four areas in 2000 (agronomy, model development, climate change and methods) to more than 20 in 2015. However, despite this explosion and expansion there is little evidence in the literature that modelling was having an impact on farmers and policy makers. We conclude with an examination of the forces shaping cropping systems model development and application. Developments in data acquisition and model-data fusion may open the way for cropping systems models to have greater impact in real-world policy or practice settings, making a meaningful contribution to future agricultural productivity and sustainability.

"… models about the world not models of the world"

"All models are wrong – some are useful"

1. Introduction

Science has always started with observation – whether it be of the natural world or the world of experiments set up to stretch the boundaries of observational opportunities. But "observation" alone has never fully satisfied scientific minds nor led to real learning about the natural world (Box, 1979). Theories of "how the world" works would grow out of observation. These theories can be set up as traditional scientific hypotheses capable of being falsified. Notions of "models" emerged early in the scientific tradition. These could be physical models that represent essential features of a real world object or system or "virtual or conceptual" models that either qualitatively or quantitatively describe functionality. In all cases, the models involve the process of abstraction − that is the translation of a real object or system into an abstract representation of that object or system. This paper is about the evolution of quantitative (or mathematical) models of plants, soils and cropping systems.

Oquist (1978) identified four "types" of research (Fig. 1). The first two focus on "how the world works", namely Descriptive and Nomothetic[1] research. These types encompass the model building domain. The other two types relate to "how to change the world", namely Policy and Action research. *Policy Research* can be viewed as development of

* Corresponding author.
E-mail addresses: Brian.Keating@csiro.au (B.A. Keating), Peter.Thorburn@csiro.au (P.J. Thorburn).

[1] The "nomothetic" approach derives from the German philosopher, Wilhelm Windelband, and involves deriving generalised laws that explain objective phenomena. Hence, the making of models and their use as predictors of system behaviour is a classic nomothetic approach.

https://doi.org/10.1016/j.eja.2018.04.007
Received 13 June 2017; Received in revised form 3 April 2018; Accepted 16 April 2018
Available online 22 May 2018
1161-0301/

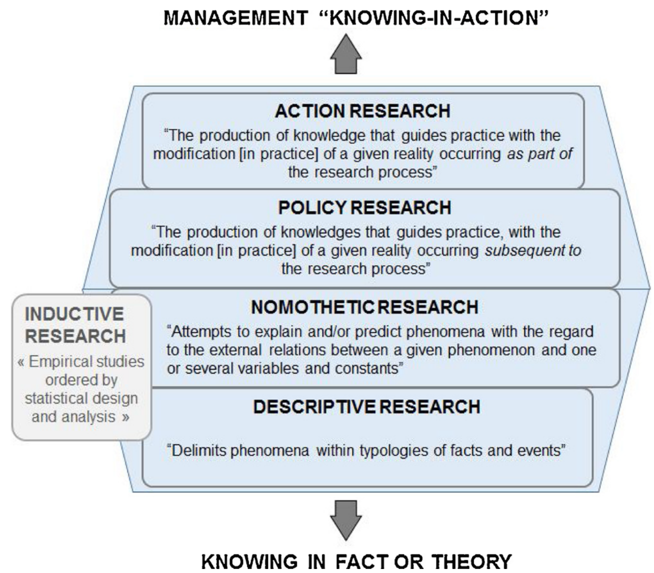

Fig. 1. A typology of research from Oquist (1978) as presented by McCown et al. (2002).

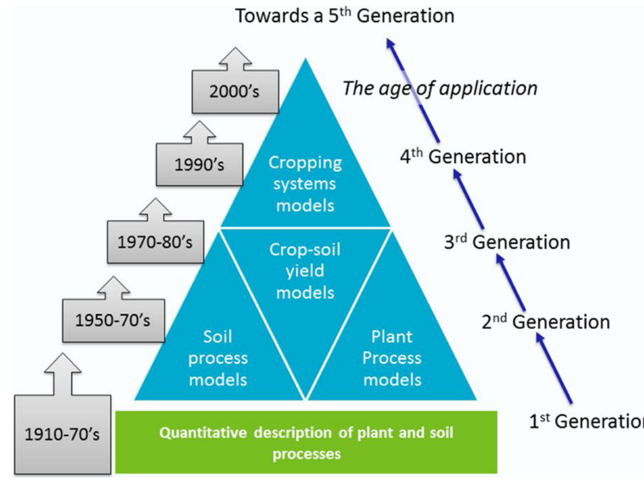

Fig. 2. Depiction of the evolution of cropping systems modelling, commencing with understanding of basic plant and soil processes to models of more integrated plant-soil interactions and ultimately cropping/farming systems.

science-based prescriptions for how a system is best be managed, while *Action Research* leads to improved system management for practitioners through direct participation in the research process. As we look back across the history of plant, soil and cropping systems modelling we see all four categories of Oquist's typology at play.

Model building in the plant and soils sciences started at the descriptive end of the spectrum illustrated in Fig. 1. It has been the "core business" of the Nomothetic research type for much of the 20th Century. What we generally think of as model applications fits under either Policy Research or Action Research. Policy here is intended to cover the widest sense of the word and has a normative meaning of "it makes sense to do something this way" – so it is a far broader concept than just "government policy". Action Research covers situations where knowledge is generated in real-life situations (the world of practice not theory) and notions of the action learning cycle (Observe – Plan – Act – Observe – Adapt) are at the core.

As we look back through the last 100 years of research into plant and soil processes we see an evolution consistent with Oquist's typology; from the descriptive/observational research to early attempts to quantify and then predict individual plant or soil processes, to more integrated plant-soil and ultimately cropping/farming system representations. In this evolution, the purpose of the modelling has also changed. From an academic motivation of quantitative plant and soil process prediction to more of a practical, mainstream set of tools deployed to help design and manage cropping system practices and policies.

We are currently in an exciting time for modelling with advances in computing, software and, importantly, data reducing or removing many of the technical obstacles that have constrained the development and application of models in agriculture. In such time of change it is instructive to look back at history of crop and cropping systems modelling. Indeed, recently Jones et al. (2016) described the factors influential in shaping the evolution of modelling in agriculture, events such as international collaborative efforts amongst scientist, external political events that created demand for crop yield predictions. In this paper we focus on the evolution of the science (and software) underpinning the models, charting the "generations" model development from Descriptive to Nomothetic (model making) research that deal with how the world works through to Policy and Action research pathways to change the world (Fig. 2). Agricultural models have enormous potential to help farmers and policy makers "change the world" and we examine the evidence from the literature the extent to which this potential has been realised and the lessons learned from that experience. We conclude this paper with some speculation about future opportunities and challenges for cropping systems models, and challenging agricultural modellers to increase efforts into making their modelling relevant to the needs of "real world" farmers and/or policy makers.

2. The classical and functional growth analysis phase (1910–1970) – the first generation

Classical plant growth analysis dates back to the early 1900s following Blackman's (1919) recognition that plant growth could progress logarithmically and could be described by an efficiency index subsequently called the Relative Growth Rate (RGR). Gregory (1917) had introduced the idea that the rate of increase in dry weight per unit leaf area, the net assimilation rate (NAR), could be used as a net measure of photosynthetic efficiency of leaves and West et al. (1920) (with mathematical refinements from Fisher 1921) completed the framing of classical growth analysis in a way that allowed the accumulation of dry matter to be analysed in terms of net assimilation rate and leaf area development, i.e.,

$$RGR = NAR \times LAR,$$

where RGR is relative growth rate (in-transformed plant weight between two harvests by the time interval between those harvests), NAR is the net assimilation rate (increase in weight per unit of leaf area and time) and LAR is leaf area ratio (leaf area/total plant weight).

Growth analysis methods evolved over time as outlined in major reviews including those by Heath and Gregory (1938), Williams (1946), Evans (1972), Venus and Causton (1979), Hunt (1982) and, more recently, the "beta growth function" of Yin et al. (2003). There was a shift from classical methods with direct calculation of growth parameters from observed data to functional growth analysis, in which curves were fitted to observed data (Poorter and Gamier 1996) and growth parameters derived. The increased availability of computers and statistical calculators in the 60′s and 70′s facilitated this growing interest in curve fitting. There was a fascination with finding functional forms in which the parameters had some biological meaning but looking back over this period it is clear that no "universal equation of plant growth" emerged with meaningful parameters and utility.

Generally the physiologists of the day were trying to dis-entangle what they referred to as "internal" controls on growth associated with plant development from external controls associated with the environment (Briggs 1928). Their interest generally lay in how these internal and external drivers manifested as differences in photosynthetic

capacity (inferred via NAR) and leaf canopy development (inferred via LAR). While Poorter and Gamier (1996) report a small number of practical applications in plant breeding, plant physiology and plant ecology, it appears the practical applications of this first half century of plant growth analysis were few and far between. However, this period of curve fitting to plant growth data and framing plant growth in terms of leaf canopy for light capture and photosynthetic capacity did lay the foundations for the crop modelling efforts that are outlined in the sections below.

One such foundation came from Watson (1947) when studying the comparative physiology of field crops at Rothamsted. Interpretation of inter-species and seasonal variation in NAR was the focus of the work, but a new parameter, the Leaf Area Index (LAI) was defined as the total one sided area of leaf per unit of ground area and it is not a surprise to us now, but it was novel in 1947, to see that LAI is a very powerful crop parameter that helps explain and predict much about crop growth. While LAR had up to that time been a measure of "leafiness" in the growth analysis, it did not translate well from single plant studies to crop canopies in which light distribution and capture by the entire leaf canopy was the driving force for growth.

With LAI as a new dimension of growth analysis, it was Monsi and Saeki (1953) who used an expression analogous to Beer's Law to quantitatively describe the attenuation of light with depth in crop canopies, namely;

$$I = I_0 e^{-kL} \tag{1}$$

where I_0 is irradiance above a canopy, I is irradiance beneath a canopy of LAI = L and k an extinction coefficient influenced by canopy characteristics most notably leaf size and angle and plant configuration.

3. The emergence of dynamic crop models (1950′s–70′s) – the second generation

3.1. Development of crop models from physiology

The foundations of dynamic simulation of crop growth can be found in the work of CT de Wit in the 1950s. In 1993, just a short time before de Wit's passing, (the late) Bob McCown and the senior author had the opportunity to ask him what got him started on agricultural simulation. De Wit replied,

> "In 1948/49 when I was a student, a new professor named van Wijk came from Shell Laboratories, where he had been an expert on distillation problems – how to get the proper oil fractions out of the distillation columns. You know that's a real operations research problem to get out of them what you want to get out of them—what to do with all the fractions. He was fascinated by the application of quantitative theories, as was I."
>
> "So, a lot of the origin of my fascination with how to quantify agriculture comes really from the oil industries. In agronomy, nobody could tell me how much a crop could maximally yield if you remove all constraints, and I found that a reasonable question. It cannot have infinite growth—it has to have a limit, and I thought we needed to know the limit. But this question was not even asked, let alone answered, and I was especially fascinated with it."

CT de Wit's early work focused on quantitative systems analysis of major components of crop growth – a physical theory to inform fertilizer placement for his doctorate in 1953, the dynamics of transpiration and crop yield (1958), competition in plant mixtures (1960), ionic balance and crop growth (1963) and photosynthesis and leaf canopy function (1965). By 1965, de Wit was publishing Fortran code to calculate light distribution and daily totals of photosynthesis to run on an "IBM 1620 computer with 20,000 storage positions". While de Wit's work was always quantitative and framed by a systems view, it was not until 1968 that his first effort at dynamic simulation modelling made use of the emerging computing power of the day (Brower and de Wit, 1968) in the ELCROS model of vegetative growth in maize. At around the same time, WG Duncan in the US was also starting to build dynamic simulation models of components of crop canopy photosynthesis (Duncan et al., 1967). These early models generally had mechanistic approaches to simulation of canopy illumination over small time steps (hourly) and leaf level photosynthesis and respiration.

During the 70′s there was an explosion in the different efforts to model plant process and crop performance. The decade began with a major review of research on agricultural productivity by RS Loomis, WA Williams and AE Hall (Loomis et al., 1971). They strongly advocated the *"need for integrative research by plant physiologists and to show how techniques of modelling and simulation are a powerful aid to such research."*

The state of the art in the first half of the 70′s was well captured in the book "Crop Physiology" edited by LT Evans (1975), summarised in the Supplementary Material. While the wheat chapter in "Crop Physiology" (Evans, 1975) was written by Australians and made no mention of modelling, it is interesting to note that the world's first dynamic simulation model for wheat emerged at the same time in Australia in a PhD Thesis (Morgan 1976).

Interest in model development and application was growing rapidly in the 70′s. WG Duncan again was a pioneer when he wrote;

> … "one can predict maize yields by correlation methods if sufficient past yield and weather history is available, but this gives little information about why yields varied. A simulation model should predict grain yields, given the same weather information, but in addition it should describe the state of the plant at any date of the growing season. … One could predict the consequences of earlier or later planting, or of irrigation at any time, or of the use of a variety with different characteristics. An important use of almost any simulator is to answer the question 'what would result if …?' – "With the simulator and historical weather records one can learn what would have resulted over past years from the use of new practices or varieties, thus accumulating valuable experience without loss of time" …. WG Duncan (1975).

3.2. Early attempts to quantify soil processes (20′s–60′s)

While we found the origins of crop models in early 20th Century plant physiology, soil models can be traced back to the agricultural chemistry of the mid19th and early 20th Century. EJ (Sir John) Russell's book on "Soil Conditions and Plant Growth" first published in 1912 is a good starting point (Russell, 1912). There have been eleven more editions since, the latest in 2012 to recognise the centenary of the original. The book starts with the prophetic (yet non-inclusive by today's standards) words of Sir John, "*In all ages the growth of plants has interested thoughtful men*". Sir John goes on to explain how the principles of plant growth in relation to soil processes were discovered by a mix of observation, experimentation and speculation. These started with van Helmont's experiments (conducted from 1577 to 1644 and reported by his son in 1652) that concluded that water was the sole nutrient required for plant growth, extended through Jethro Tull's theory that it was the minute particles of soil, loosened by moisture that constituted the "proper pabulum" of plants. There were many other stunning discoveries and spectacularly incorrect theories of the dynamics between plants and soils over the years that followed. One of the biggest controversies not put to rest till Liebig's writings in the mid 1840′s was whether plants obtained their carbon from the soil or the air. Sir John Russell recognised JB Boussingault as the founder of modern methods of agricultural science, based on his careful field experimentation on his farm at Bechelbronn in Alsace around 1834. Sir John's own establishment when he wrote the first edition in 1912 was Rothamsted Experimental Station, established by JB Lawes when he appointed JH Gilbert as an agricultural chemist and started one of the most productive

scientific collaborations of all time that extended for the next 57 years and established the principles of crop nutrition and in doing so laid the foundations for modern scientific agriculture. Rothamsted Experimental Station and some of its earliest field experiments continue to the present day and some of these field experiments established in the 1840′s have been used for model building and testing (Jenkinson 1990). Rothamsted is also important in our story of the evolution of models in agriculture, because it was also the birthplace of the theory and practice of statistics in agricultural research with the likes of RA Fischer and successors.

Akin to plant growth modelling, the foundations for soil-focused models lay in the quantitative analysis of individual soil processes or plant response to soil conditions. Over time, knowledge grew of the nature of these functional relationships and interest grew in understanding their interactions with multiple soil factors and with plant and environmental conditions. The 1950 eighth edition of EJ Russell's “Soil Conditions and Plant Growth” contained 36 chapters on every conceivable dimension on the topic, but there was no chapter that integrates the component insights and certainly no mention of predictive models and their application to the study and management of soils. The closest this edition got to modelling was to report Penman's work on evaporation from free water surfaces, bare soil or an actively growing crop using energy balance and meteorological conditions. There is one figure (Fig. S1 in the Supplementary Material) comparing the predicted and observed time course of evaporation from a turf soil at Rothamsted.

More of a US perspective on “Soil-Plant Relationships” in the 1950′s comes from CA Black's book of that title, first published in 1957 and updated (the 2nd edition) in 1967 (Black, 1967). There is little evidence in the 2nd and subsequent editions that modelling approaches were starting to emerge in the 60′s in this community of soil-plant research. In the water and nitrogen chapters, where one might expect to see the evidence of integrative or dynamic modelling treatment there was none − the focus was on essentially descriptive treatments of individual soil, plant or plant-soil processes.

Yet we know that models were starting to be applied to soil water studies around these times – but perhaps not reaching into the mainstream agricultural or soil science faculties. The evolution of models of soil processes in the 1950′s actually followed a similar trajectory to that outlined above for crop models. At around the same time CT de Wit was exploring mathematical descriptions of plant systems, C.H.M. van Bavel was exploring mathematical approaches to the soil water balance.

Referring again to the interview with CT de Wit, when Bob McCown referred to the pioneering simulation study by van Bavel (1953) on supplementary irrigation needs for tobacco production in the eastern states of the US, which he felt utilised a model based – operational research approach, Prof. de Wit laughed, and said,

> “Where do you think he trained? We both came from van Wijk's laboratory!”

Some of the earliest applications of computers to soil water balance modelling came from Australia, where agriculture was still in a pioneering stage and assessment of agricultural potential of vast areas of the country, particularly in northern Australia, could not be done via direct experimentation. Hence, soil and climate data were used to assess potential for plant growth. This work started with RO Slatyer and team's efforts at characterising the major terms in the water balance through measurement and modelling. Slatyer (1959) focused on measuring terms in the soil-plant-atmosphere continuum and some simple (non-computer based) water balance calculations. Early reports from CSIRO's Land Assessment Unit were using simple water balance models (Slatyer 1960, 1964; Fitzpatrick and Arnold 1964). By 1965, Slatyer was reporting to UNESCO meeting on “Methods of Agroclimatology” on extensive water balance model analyses to aid both assessment and management of agricultural and natural ecosystems (Slatyer 1965).

Computer based models however did not feature in this reporting formally till Keig and McAlpine (1969)'s publication of the FORTRAN based “WATBAL” in 1969, which ran on a Cyber76. However, in the introduction to this report the authors explain the history. “*The water balance model on which the system is based was originally formulated by* Slatyer (1960)*”* … *“In 1962, a program was written for an IBM1620 system and later modified to run on CDC 3600 system*”. Fitzpatrick (1969) elaborated the model to express results in terms of “drought” and “growth period” periodicities and probabilities. These were the foundations of the Keig and McAlpine's WATBAL program whose utility was demonstrated by McAlpine (1970) in the assessment of pasture growth and drought incidence. These efforts in the late 60′s in Australia were some of the earliest practical applications of computer-based plant-soil models. Other early numerical simulations of layered water balance came from van Keulen and van Beek (1971) written in CSMP as applied to experimental data in Stroosnijder et al. (1972).

In terms of early quantitative treatments of crop response to soil nutrient supply, we turn to de Wit again (de Wit, 1953) for his elegant graphical analyses of relationships between N application and N uptake, N uptake and grain yield and N application and grain yield (see van Keulen 1977 for an extensive treatment of this framework). While these early efforts were static, they essentially frame what was to become the dynamic soil nutrient supply and demand models of later years (see next section).

4. The rapid proliferation in crop-soil models – 70′s and 80′s – the third generation

4.1. Evolution of coupled crop-soil models

While the foundations of cropping systems models were set down in somewhat distinct efforts emerging out of plant physiology for the crop components and soil science for the soil water and nitrogen components, these efforts started to come together in many different ways in the 1970′s and 80′s. At that time we saw the development, release and sometimes on-going support and application of a great many “crop models” as we interpret the term today. Such models generally had both dynamic plant and soil simulators and aimed to have sufficient mechanistic treatment of processes to have general application across a range of environments and management regimes. In many cases, some of the finer mechanistic detail of the initial modelling efforts tended to be put aside for simpler, less data hungry approaches – sometimes called functional, phenomenological or statistical approaches (Thornley, 1976). Thornley distinguishes between the mechanistic model which is “*couched in terms of mechanisms of how the parts of the system work together as in a machine*” and the empirical model which “*simply describes the data and does not give rise to any information that is not contained in the data*” (Thornley, 1976). In practice, the distinctions are often blurred. Models structured around a mechanistic hypothesis or theory often end up using empirical or phenomenological equations to describe sub-components or individual processes.

One good example of this evolution in the mechanistic detail in crop models is the evolving treatment of canopy photosynthesis. While the early models of de Wit and Duncan were rich in detail on leaf photosynthesis and plant respiration, the models that evolved into widespread usage in the 80′s generally took the measure of canopy light capture (Eq. (1)) first described by Monsi and Saeki in 1953 times a measure of the efficiency with which intercepted light is utilised for dry matter production (ε), to provide a measure of crop growth rate (CGR);

$$CGR = I_0(1\text{-}e^{-kL})\ \varepsilon$$

where ε is inferred from the slope of a relationship showing CGR as a function of absorbed light and has the units of g dry matter per MJ photosynthetically active radiation absorbed (referred to as the Radiation Use efficiency (RUE) in many models).

This generation of models were neither fully mechanistic nor fully empirical. They were structured around the key mechanisms

understood to drive plant development, growth and yield and key processes understood to be important in soils (generally soil water and nitrogen balance). It was never a case of not knowing other factors could influence crop performance (such as nutrients other than nitrogen) – but more a case of keeping models as simple as possible for the intended purpose (such as predicting yield in relation to crop characteristics and management, soil factors and weather. In other words the maxim was – we were building "*models about the world, not of the world"* and *"All models are wrong but some are useful"*.

An early effort to combine a crop growth simulation model with a soil water balance model came from Australia, when Berndt and White (1976) were looking at the impacts of land use practices on water yield and quality. DeCoursey (1980) combined the cotton growth simulation model GOSSYM (Baker et al., 1983) with a hydrologic model to explore management interactions between tillage, hydrology and crop growth. Stinson et al. (1981) combined a sorghum crop simulation model (Arkin et al., 1976) with hydrologic and sediment models developed by Williams (1978) to explore ratoon cropping of sorghum on water quality and quantity and crop yield.

Around this time coupled models of crop growth simulation and nitrogen dynamics were also emerging. One of the earliest came from Jones et al. (1974) who combined a simple soil-N balance model with the plant-N requirements of the SIMCOT cotton model. Not long after this, models were being developed with increasingly detailed descriptions of the nitrogen cycle, i.e. moving from single "pools" of organic matter with zero-order process (i.e. a constant decomposition rate) to multiple "pools" of organic matter using first-order rate kinetics. One these new models was the nitrogen-tillage-residue-management (NTRM) of Shaffer et al. (1982). The intense interest in nitrogen modelling expanded rapidly, leading to increased numbers and comparisons of different nitrogen models. An early comparison happened in a workshop in early 1983 involving six different models (De Willigen and Neeteson 1985) followed by a workshop in 1990 including 14 models (De Willigen, 1991), extending to more recent times with 18 models compared in a workshop in 2004 (Kersebaum et al., 2007). This interest in comparing models was mirrored the soil organic matter modelling community[2] (Smith et al., 1997) and, more recently, the crop modelling community (Asseng et al., 2013; Bassu et al., 2014; Marin et al., 2015; Li et al., 2015). As well as nitrogen dynamics, interest was also growing rapidly in simulation a wide arrange of crop stresses, including other nutrients, water, soil salinity, soil strength, soil aeration in the context of radiation and temperature environments.

In 1981, a monograph of the American Society of Agricultural Engineers was published focused on "Modifying the root environment to reduce crop stress" (Arkin and Taylor 1981). The editors wrote of the emergence on integrated crop-soil models and they were clearly excited by the possibilities on the horizon. They wrote:

> "Unlimited possibilities exist for application of combined or integrated models"…. "Systems simulation models that include stresses dealt with in this monograph are becoming available. Sensitivity analyses, validation and documentation are needed before they can find general acceptance. Implementation will depend on their ability to assist in analysing complex management decisions".

In 1981, the potential for widespread use of crop-soil models was seen by many but it would be another decade or two before widespread availability and use of crop-soil models was the norm in agricultural research. The modelling effort that had one of the most significant impacts over this period started with the umbrella name of CERES – the "Crop Environment Resource Synthesis" (Basso et al., 2016b). Jones et al. (2016) have recently explained some of the history of agricultural systems models and they report that the motivation to develop the CERES models – with spillovers to many other modelling efforts in the 70′s and 80′s – came from the US Government's concerns over dynamics of world wheat markets triggered by Soviet Union purchases in 1972. CERES-Maize and CERES-Wheat (Jones et al., 1983; Jones and Kiniry, 1986; Godwin et al., 1983) emerged from these efforts in the early to mid-80′s. A critical achievement of the CERES effort was to link up comprehensive models of plant growth and development with a similar level of functional detail and explanatory power in the soil water and nitrogen balance. The WATBAL model of the CERES family derives from Joe Ritchie's water balance modelling (Ritchie 1972, 1973) and it remains unclear the extent to which it drew on the WATBAL of Kieg and McAlpine mentioned above. Doug Godwin worked on the soil/plant nitrogen sub-models (Godwin et al., 1983) and the annual pasture model PAPRAN (Seligman and Van Keulen, 1981) was always recognised as the source of inspiration for the soil nitrogen routines. The "GRO" models for soybean and peanuts (Wilkerson et al., 1983; Boote et al., 1986) appeared around the same time.

At around the same time these "third generation" crop-soil models were being published and released to the public domain, USAID had funded a project on agro-technology transfer called IBSNAT (International Benchmark Sites Network for Agro-technology Transfer) (IBSNAT, 1984; Silva and Uehara 1985). The notion, simply stated, was that agro-technologies could be evaluated under well characterised soil/climate conditions and application domains for appropriate technologies (e.g., varieties and practices) determined using crop-soil models. The development of minimum data sets for model development and testing (Nix 1983) and the extensive training program in model application associated with the CERES and GRO modelling efforts (which later merged into the Decision Support System Agrotechnology Transfer (DSSAT) model, Jones et al., 2003) across the developed and developing world were major factors contributing to the profound impact of these efforts. Concepts such as minimum data sets for model development and testing still live on (Kersebaum et al., 2015), spurred by interests within the AgMIP (Rosenzweig et al., 2013) and European MACSUR (Rotter et al., 2013) communities, and many modelling groups are still active in providing training in modelling.

Looking back on the early 1980s, it is clear now that the IBSNAT effort was redefining the entire concept of agronomy towards the end of the 20th Century. IBSNAT was a broad international collaboration including US Universities (lead from Uni of Hawaii), ARS staff of USDA, Canadian, Australian scientists, CGIAR Centres and a diverse range of national collaborators. Prof Henry Nix, an Australian who came out of the same land use research group of Slatyer, Fitzpatrick and others that pioneered water balance modelling in the 1960′s (e.g. Fitzpatrick and Nix 1970) explains (Nix 1985) how "*while-peg agro*nomy" has been the entrenched paradigm of agricultural research in which statistical analyses is used to detect significant differences between treatments at representative sites and the results extended by analogy to equivalent sites. In explaining the inadequacies of conventional agronomic experiments which still dominated the profession throughout the 80′s and 90s, Nix (1985) stated;

> "Statistical differentiation of treatment effects, where major environmental controls or interactions are ignored or assumed constant across all treatments is not conducive to a deeper understanding of process nor to the development of general functional relationships".

Nix (1983, 1985) proposed a "systems research strategy" (Fig. 3) that placed crop system models and resource databanks as key tools in framing research activity and interpretation.

Nix (1985) concluded:

> "Alternative strategies of agricultural research and development are becoming feasible. Computer based systems of data capture, storage and retrieval can remove the straitjacket of single static multi-

[2] The development of soil organic matter modelling has been charted by authors such as Manzoni and Porporato (2009), Sierra et al. (2012) and Powlson et al. (2013).

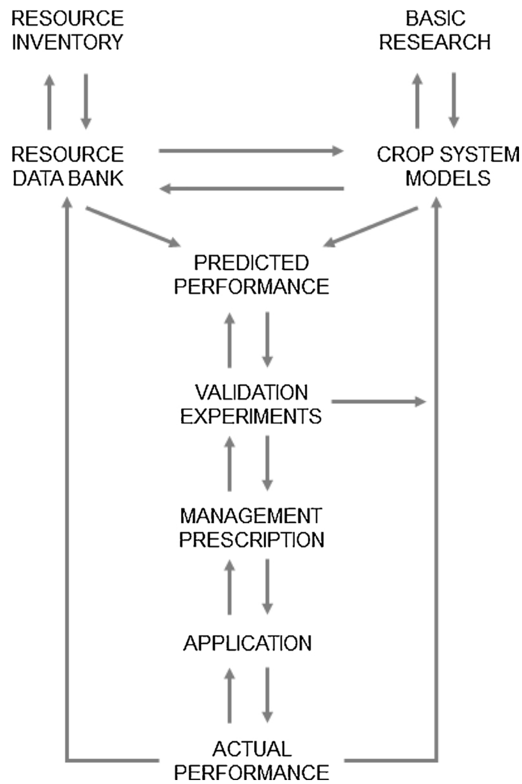

Fig. 3. Components of a systems research strategy as devised by Nix (1983, 1985).

purpose climate soil and/or land classification."

4.2. The move towards Farming Systems Research

While much progress was being made in the 70′s and 80′s in the construction of crop-soil models and the "hype" was building in terms of their potential to transform agricultural research methods, there were other important developments in train that ultimately would intersect and hybridize with the crop modelling effort. Farming Systems Research (FSR) – a vision to better connect "On Station" technical research with "On Farm" adaptive research (Fig. 4) – emerged in the late 70′s (see Dillon, 1976) and early 80′s (see Collinson 1982, Dillon and Virmani 1985) in response to a growing view that agricultural research was losing its relevance to the needs of "real world" farmers, either because (a) the research is misdirected because researchers misperceive farmers needs or (b) farmers cannot perceive the relevance of the research results. FSR programs became a major components of most international research and development programs in CGIAR[3] Centres and most major development donor programs such as USAID and significant effort went into training programs and methodological guidelines (e.g., Shaner et al., 1981).

The approach did generate new and improved insights into the real world constraints under which farmers operate and the better recognitions that these constraints go well beyond the technical issues in crops and soils that had been the concern for much agricultural science to include human systems issues, as illustrated in Fig. 5.

Problems arose however with how to interpret the on-farm experiments with a large number of controlled and uncontrolled variables interacting and how to generalise the results across seasons and soils. The early proponents of FSR were aware of these potential challenges

[3] CGIAR is a global research partnership on food security (http://www.cgiar.org/). It operates through 15 research centres located in the major agro-ecological zones of the world.

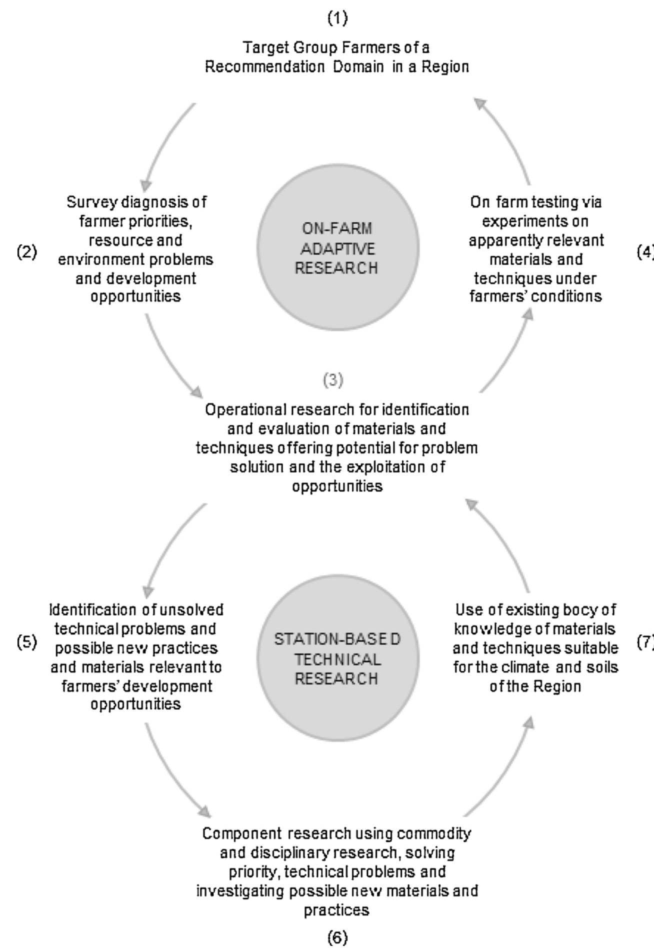

Fig. 4. Schematic view of Farming Systems Research methodology, after Collinson (1982).

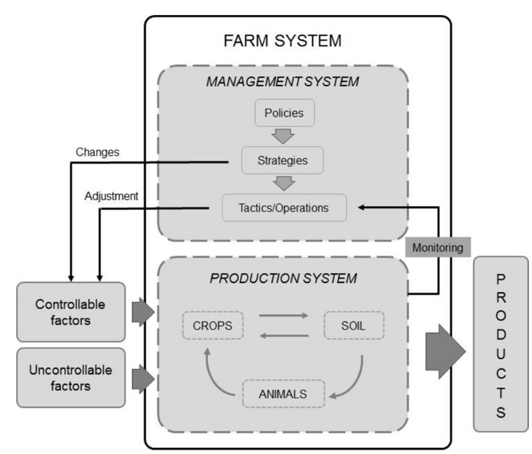

Fig. 5. A simplified model of the farm system, depicting management as normative, instrumental, and cybernetic, adapted by McCown et al. (2002) from Sorensen and Kristensen (1992).

and Dillon and Virmani (1985) wrote:

> "The newly evolving field of dynamic systems models would seem to have great potential for handling the complex interaction that characterise on-farm production. If this is so, such models should help in over-coming the problem of location specificity. Data collected from multi-disciplinary investigations across different agroclimatological zones could be used effectively in the development of

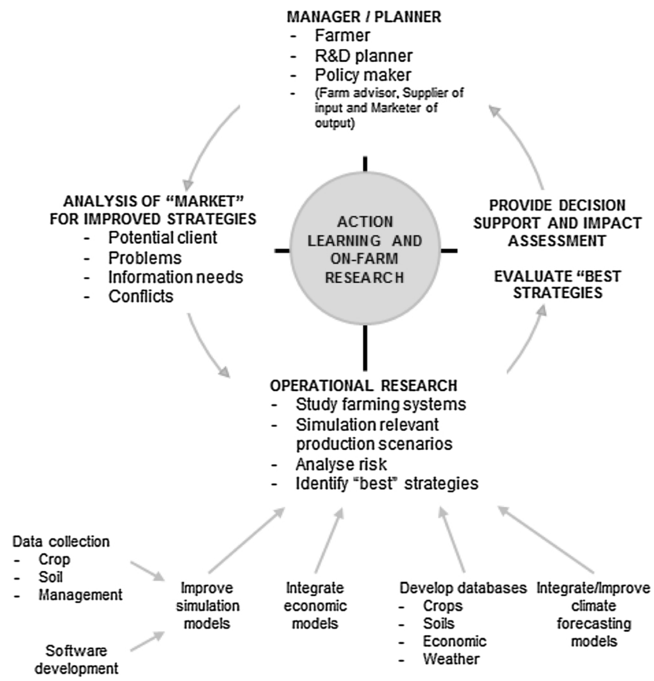

Fig. 6. The systems research framework that builds crop-soil modelling into a Farming Systems Research paradigm (after McCown et al. 1994). Note – "operational research" in this figure replaces the "On Station Technical Research" in the Collinson "figure-8 diagram" (Fig. 3).

> 'weather-driven' crop production models which would provide a vehicle for guidelines for system manipulation and appraisal under varying locales".

This proposition put forward by Dillon and Virmani in 1985 is exactly what was explored by the Australia-Kenya Dryland Farming Systems project from 1985 to 1992 (McCown et al., 1992; Carberry 2005) and beyond that in India (Dimes and Revanuru, 2004) and southern Africa (Whitbread et al., 2010) throughout the 90′s. The newly released CERES-Maize was tested on maize growth and development data collected under a very broad range of crop management, water and nitrogen regimes. The model needed to be refined and further developed to address the low yield and high stress environments encountered (Keating et al., 1990, 1992a,b,c) but it did indeed prove very useful in exploring production possibilities in response to on-farm constraints (Keating et al., 1992a,b,c; McCown and Keating 1992). The approach to combining a crop-soil simulator with the Collinson FSR methodology was developed by McCown et al. (1992, 1994) and McCown and Keating (1992), as summarised by Fig. 6.

The Kenya work with a derivative of CERES Maize (called CMKEN) produced new insights into the opportunities to use modest nutrient inputs and adapted agronomic practices to move a low yield subsistence farming system towards a more productive and sustainable state (Keating et al., 1991, 1992a,b,c).

Beyond Kenya, these participative action research (PAR) approaches involving on-farm research aided by crop-soil simulation modelling gained wider application in India (Dimes and Revanuru, 2004), southern Africa (Whitbread et al., 2010) during the 1990s and 2000s. In more recent years, we see examples of this approach all over the world – including in developed agricultural systems as has proved to be the case in Australia (Farmscape – Carberry et al., 2002). An international symposium in Brisbane Australia in 1990 showcased these emerging applications of crop-soil models, stimulated in large part by the modelling work in Kenya and companion programs in northern Australia (Carberry and Abrecht 1991). Titled "Climatic Risk in Crop Production – Models and Management for the semiarid Tropics and Subtropics" (Muchow and Bellamy 1991), this meeting was a turning point: All the discussion of the potential for crop modelling in the 1980s was replaced by tangible evidence from around the world on the insights that were being generated – particularly in situations where agriculture operated under highly variable climates.

The Australians were not the only group exploring ways in which crop-soil models could be harnessed to better support agricultural development. A number of key international meetings during the early to mid–90 s led to shared experiences and joint efforts under frameworks such as IBSNAT and later ICASA. The Dutch legacy of de Wit was strong with the series of meetings titled "Systems Approaches to Agricultural Development" in Thailand (Penning de Vries et al., 1993), Philippines (Teng et al., 1997) and Peru (Kropff et al., 2001).

5. From crop models to cropping systems models (90′s) – the fourth generation

The evolution of FSR, in parallel with the proliferation of coupled crop-soil models shaped subsequent model developments. Although crop-soil models of the late 80′s evolved over 20 years from partial models of individual plant processes (such as canopy photosynthesis and vegetative growth) to fully specified models of crop growth and yield in relation to water and nutrient (generally nitrogen) supply, they were still separate models for separate crops. DSSAT was first released in 1989 (Jones et al., 2003) and this package brought the CERES and GRO models together into a single user interface with supporting model input and output facilities – but they were separate crop models, each with their own soil routines and no way of realistically configuring a "cropping system".

Over the 1985–1990 period, the Australia-Kenya Dryland Farming Project had been working with CERES-Maize to explore strategies to improve the productivity of farming in semi-arid maize based farming systems (McCown et al., 1992). CMKEN was the resultant model adapted to address features of the low-input farming system that could not be addressed by the original CERES-Maize (Keating et al., 1991, 1992a,b,c). Examples of functionality added to CMKEN included crop death due to extreme stress, and features to represent the dynamics of farmer management such as an ability to thin maize populations, routines to enable sowing that was responsive to weather conditions (rather than on a fixed sowing date as in the original model), dynamic management of inputs that was conditional on seasonal conditions, etc. Ultimately the focus of this work was on soil fertility dynamics over time and the cumulative impacts of crop choice and management (including intercrops, weeds) on soil fertility and soil erosion (Keating et al., 1992a,b,c). Some of these "systems capabilities" were super-imposed on the CERES-Maize model structure, but by 1990 it had become increasingly obvious to the model specifiers, users and software engineers that the "spaghetti FORTRAN" code that evolved was too complex and unstable to provide a long-term foundation for a cropping systems simulator. Most importantly, it became evident that the entire approach to model conceptualisation and software architecture needed to be reconsidered. Instead of trying to link up different crop-soil models such as in the early DDSAT, a robust and capable systems model needed to start with a soil simulation and build from there. McCown et al. (1996) explain:

> "The key concept is the central position in the model of the soil rather than the crop, in spite of the fact that the output generally of greatest interest is crop yield. Changes in the status of soil state variables are simulated continuously in response to weather and management. Crops come and go, each finding the soil in a particular state and leaving it in an altered state. All crops share the same soil and aerial space in which various processes take place, e.g. soil water and nitrogen transfers and transformations, surface residue decomposition, and radiation interception. This structure allows ready simulation of the effects of one crop on another via its effects on the soil, in both sequences and mixtures of crops."

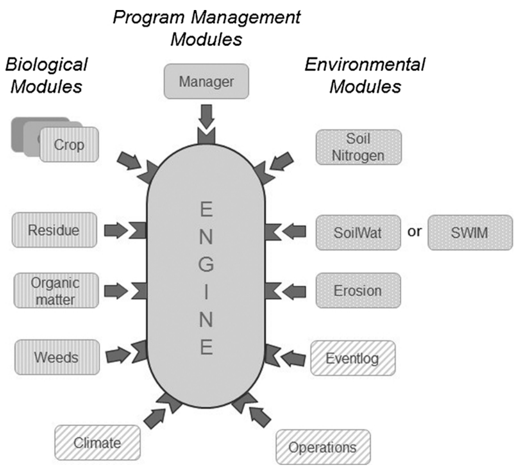

Fig. 7. Structure of APSIM as published by McCown et al. (1996).

There were other "land systems" models available at the time that had this same "soil centric" view, such as EPIC (Williams et al., 1989), NTRM (Shaffer et al., 1982) and PERFECT (Littleboy et al., 1992), but none dealt with the crop components in an adequately yield-sensitive and management-responsive way, like that which was established in the CERES approach (see Steiner et al., 1987; Probert et al., 1995).

The need for a soil-centric cropping systems simulator led to the development of the Agricultural Production systems sIMulator (APSIM) in the early 90s. The original structure of the APSIM model as published in 1996 is reproduced in Fig. 7.

Key (and initially unique) features of APSIM include (as summarised by Holzworth et al., 2014a) abilities in simulation of intercrops, weeds, biotic constraints, crop-livestock interactions, manure and phosphorous in low input farming systems, multi-paddock simulations with complex crop rotations, erosion-productivity interactions, greenhouse gas and water quality impacts, elaborate crop-surface water storage simulations, forest and agro-forestry configurations. APSIM's flexibility always resided in its core architecture – "*Crops* [and animals and trees and weeds and seasons and managers] *come and go, each finding the soil in a particular state and leaving it in an altered state*".

The DSSAT model and a host of other crop models, or increasingly cropping **systems** models emerged and evolved over the 1990–2000 period. DSSAT evolved to improve its functionality in cropping systems simulation and by 2003 it was described as a modular cropping systems simulator (Jones et al., 2003). Other cropping system simulators emerged including Cropsyst (Stöckle et al., 2003) and STICS (Brisson et al., 2003). The Dutch models were still in use (van Ittersum et al., 2003) but the Wageningen group never went down the route of supporting a major cropping systems simulator like APSIM or DDSAT. The three groups continued international connections via the ICASA Consortium. Some from Wageningen pursued significant and longer term modelling efforts on related topics, such as the NUANCES whole farm modelling approach (Giller et al., 2011) and the SEAMLESS effort which focus more on how a diverse range of models could be used for spatial assessments of agricultural policy choices in the European Union (van Ittersum et al., 2008).

6. The coming of age – model applications and impacts in the 00's

6.1. The scale of application

A major review published at the start of the second century of crop-soil modelling in Advances in Agronomy (Matthews et al., 2002) illustrates the explosion in publication output based on applications of crop-soil models. Around that time an important international meeting on "Modelling Cropping Systems" took place in Florence (in July 2001).

Table 1
Citation data on the crop/cropping systems models published in the 2003 special issue of European Journal of Agronomy (based on Thompson Reuters Web of Science search on 16/02/2016).

Paper/Model	Total citations of the EJA 2003 paper	Citations of the EJA 2003 paper since 2013 (and % of total)	Total number of papers[a]	Total citations[a]
Wageningen crop models	251	59 (24%)	313[b]	4519[b]
DSSAT	937	292 (31%)	590	5929
APSIM	876	264 (30%)	701	9909
CropSyst	453	140 (30%)	203	3085
STICS	329	94 (29%)	437	6747
Total[c]	2846	849 (30%)	2253	30255

[a] Papers with model name in title or topics (including abstracts).
[b] Based on three searchable models, WOFOST, SUCROS and LINTUL.
[c] There may be some double counting of papers that report on more than one model.

A feature of the conference was the major focus of contributed papers on model applications in agricultural practice and policy domains. A special issue of the European Journal of Agronomy (EJA) was published from that meeting containing updated reference papers for the key cropping systems simulators available at the time, that is Wageningen crop models (van Ittersum et al., 2003), DSSAT (Jones et al., 2003), APSIM (Keating et al., 2003), Cropsyst (Stöckle et al., 2003) and STICS (Brisson et al., 2003). Table 1 shows the citation records for the five key crop or cropping system models described in their reference publication in the 2003 EJA special issue. Note these records are not a perfect record of model usage as some models may be referenced via earlier or later papers; e.g. APSIM now has three reference citations, McCown et al. (1996), Keating et al. (2003) and, most recently, Holzworth et al. (2014a) reflecting the evolution of model capabilities and versions. All five models or modelling platforms have received extensive use in the 2003–2016 period with the EJA papers cited 2846 times (Table 1) and with no signs of any diminution of citation rates (Fig. 8). An alternative approach to assessing model usage is to conduct a global search through the Web of Science databases for the model name in the title and topics (including Abstract). The results of this are also shown in Table 1 identifying 2253 papers in total that meet these criteria and a total of 30255 citations for these papers. APSIM and DSSAT are the most frequently used or cited crop models making up over half of the papers or citations – noting there is still significant use of all the model platforms.

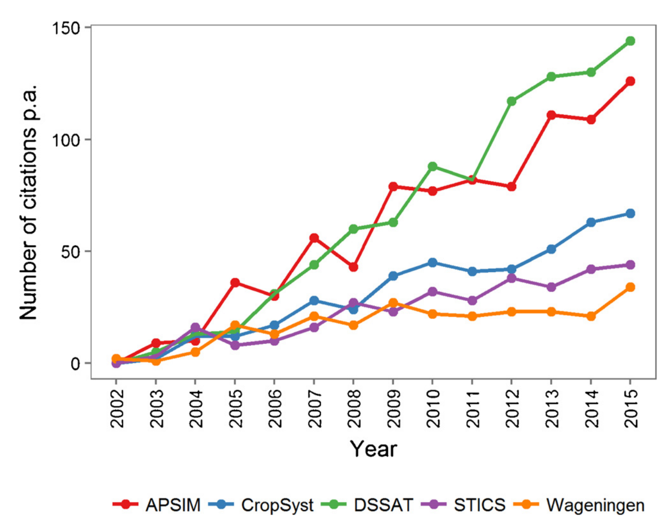

Fig. 8. Trends in citations data on the crop/cropping systems models published in the 2003 special issue of European Journal of Agronomy (volume 18, issues 3–4), based on Thompson Reuters Web of Science search on 16/02/2016.

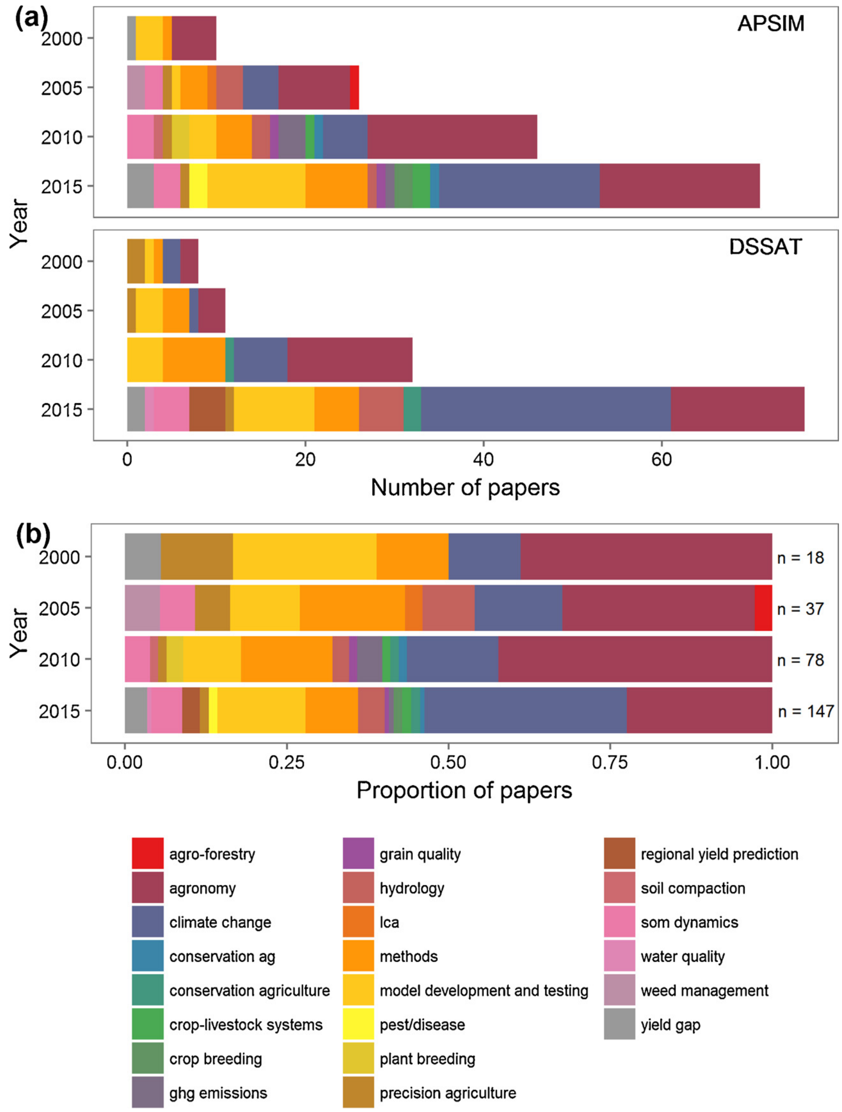

Fig. 9. Summary of papers from WoS for 2000, 2005, 2010 and 2015: (a) number of papers with APSIM or DSSAT in title, topic or abstract classified against fields of investigation, and (b) proportion of papers for APSIM and DSSAT (combined) classified against fields of investigation.

We have attempted to examine the focus of this explosion of publication and citation activity – and how this focus has changed over the 2000–2015 period. To reduce the size of this task to something more manageable given it involves examining all papers prior to classification, we have focused on the two models that have received the most attention (DSSAT and APSIM, Table 1) and looked at 4 whole years, namely 2000, 2005, 2010 and 2015 (Fig. 9a). Over that time, there has been a large increase in the type of application of these models. In 2000 the models were mainly being applied in four fields; agronomy, model development, climate change and methods; with three (of 18) papers in two other fields (precision agriculture and yield gaps) for the two models. In subsequent years models have been applied in 22 fields. In 2015, climate change had replaced agronomy as the largest application field compared with 2000, and papers on methods or model development had declined from 33 to 22% of applications (Fig. 9b). These trends show a move over time from Descriptive or Nomothetic research to Policy and, to some extent, Action research according to Oquist's typology (Fig. 1).

6.2. From application to impact

While there was an explosion (in numbers) and expansion (in applications) in publication outputs based on crop-soil models from 2000 to 2015 (Fig. 9), questions were being asked whether modelling was having an impact on farmers and policy makers (Matthews and Stephens 2002; McCown 2002). Matthews et al. (2008) went as far as posing the question: "Wither Agricultural DSS?" The above analyses (Fig. 9) clearly show that activity on modelling has not wasted away; however the question of what impact all this activity has had on farmers and policy makers is still relevant.

There are some clear impacts of modelling on policy. The dramatic increase in papers from 2000 exploring impacts of climate change and adaptation options (Fig. 9b) reflects the global importance of that issue to agricultural policy and, perhaps, the "demand" for information for the IPCC Assessment Reports. Not surprisingly, modelling-based predictive studies are a significant source of information for these reports (Porter et al., 2017). A more specific example of cropping system modelling having an impact in government policy is the protection of the Great Barrier Reef in Australia from the impacts of agricultural pollutants discharged from adjacent catchments. Crop models are embedded in a catchment modelling framework (Carroll et al., 2012) that is used to both shape policy on improving farm management (i.e. grants to farmers, support for market based approaches, regulations) and evaluate progress of improved management towards meeting targets for

reduce discharge of pollutants from the catchments (Kroon et al., 2016).

In more commercial contexts, crop modelling is increasingly used in commercial plant breeding programs as a means of incorporating biological understanding into the programs to enhance genomic prediction methods for breeding and variety recommendations (e.g. Technow et al., 2015; Cooper et al., 2016; Messina et al., 2018). These advances are based on incorporating into crop models functional relationships between environmental variables and traits that influence genetic variation for yield and agronomic performance, then integrating the model into whole genome prediction methodologies. At the scale of the farm business, examples of the impact of cropping systems modelling are more diffuse. Robertson et al. (2015) reviewed the application of cropping systems models in Australian grains production and highlighted 10 examples of innovation in cropping that were underpinned by modelling. These included: incorporating seasonal climate forecasting into on-farm decision making (Hayman et al., 2007), aflatoxin management in peanuts (Chauhan et al., 2010), planting long-season crop varieties to increase sowing opportunities (van Rees et al., 2014), and the use of Yield Prophet® (Hochman et al., 2009) to support tactical crop management in ~2000 fields by a network of > 600 users (farmers, consultants and extensions staff). Yield Prophet®, a derivative of the FARMSCAPE program (Carberry et al., 2002), has become an exemplar of model application in participative action learning settings in Australian agronomy. While Robertson et al. (2015) present a good case for the benefits that are being derived by Australia grains production from crop modelling, examples of this type of evaluation are rare.

What has been learnt from the Australian experience of applying models to assist farm management? Application efforts over the past 15 years have been supported by developments in theory and collection of empirical data on the social aspects of model application in agriculture that have provided insights into success factors in model application. Hochman and Carberry (2011) identified a number of desirable characteristics of tools to support farmers' management. These included:

- Having a plan for delivery of the tool beyond the initial development period.
- Tools need to be embedded in a support network consisting of farmers, consultants and researchers.
- Tools should aim to educate farmers' intuition rather than replace it with optimised recommendations.
- Tools should enable users to experiment with options that satisfy their needs rather than attempt to present "optimised" solutions.
- Tools stand on the quality and authority of their underlying science and require ongoing improvement, testing and validation.
- Development should not commence unless it is backed by marketing information and a plan for delivery of the tool beyond the initial development period.

The third and fourth points (elaborated on by McCown et al., 2012) show that the value of models to farm management, critically, is in facilitating learning more than providing answers. Predictions promote discussion and questioning leading to new insights. In this context the model is acting as a "boundary object", facilitating a connection between farmers and advisors, extensionists and researchers to co-create knowledge (Jakku and Thorburn 2010). This vision of model applications being a process to "facilitate co-learning" rather than "produce answers" provides a more sophisticated and humble vision of the benefits derived from modelling (Thorburn et al., 2011) compared with the "used/not used" framing of earlier evaluations (McCown 2002).

The Australian experience of cropping systems model application has been clearly targeted at influencing farm management. However, as described above, models applications have had impacts on formulation and evaluation of policies. It is tempting to think of this impact pathway as, perhaps, a more one-way and linear one – researchers publish an analysis the results of which are incorporated into policy. The reality is that the formulation of policy draws on many sources of information and is influences by many outside considerations; it is no less a "human" process than farm management. Not unexpectedly, many of the many of the social elements identified in application of models on farms are also seen in the development of policy (Batie 2008; Sterk et al., 2009; Matthews et al., 2011). Thus model applications in policy contexts are likely to "facilitate co-learning" more than "produce answers".

7. The future – towards a fifth generation

Looking back over 100 years of plant and soil science one can't fail to be impressed with how far we have come with our capabilities in quantitative analysis of crop-soil systems. The foundations were laid over the first fifty years with an accumulating body of knowledge on plant and soil processes that were was progressively captured in quantitative relationships. Individuals like Blackman, Gregory, West, Watson, Penman, Monsi and Saeki made landmark contributions. de Wit stands out for establishing a more comprehensive systems analysis and modelling tradition – a decade or more before others like Duncan, Loomis, Penning de Vries and van Keulen took on these approaches and made their own rapid advances. Slatyer was a real innovator in computer based water balance modelling building on van Baval's pioneering work. Fitzpatrick, Nix, Ritchie and Jimmy Jones were all making key contributions in the late 60′s and 70′s. The IBSNAT project and CERES/GRO effort over the 70′s and 80′s from Joe Ritchie and Jimmy Jones and a big team took crop modelling into the mainstream – with comprehensive crop-soil models available for groups around the world to get started in the modelling tradition. This evolved to DSSAT and ICASA and remains a major force in mainstream crop-soil modelling today as reflected in the AgMIP (Rosenzweig et al., 2013) and MACSUR (Rotter et al., 2013) communities. The APSIM effort was kick started with CERES but the innovation there was to completely rethink and re-engineer crop models to be farming systems simulators. That too remains a strong on-going effort.

Despite a well justified sense of satisfaction with how far crop-soil modelling has come since de Wit in the 50′s, there have always been critics of modelling approaches. Passioura's (1996) contribution on "Simulation Models: Science; Snake Oil, Education, or Engineering?" remains a timely reminder of the need to maintain a rigorous scientific method and not let model development and use degrade into an unproductive convoluted and cumbersome curve fitting exercise. But retreating to the statistical safety but frequent irrelevance of the ANOVA to progress understanding and better management of complex and variable crop-soil systems is not the answer, as Nix (1985) eloquently reminded us in the 80′s. Recently, Soltani and Sinclair (2015) took aim at issues of complexity, transparency and robustness in present day comprehensive crop-soil models. They raise valid points around the clarity and currency of model documentation and sometimes ambiguity that exists in processes of parameter estimation (what should users "fit" and not change and how?). The performance of all the models independently tested (DSSAT, APSIM, CropSyst and SSM-wheat) was surprisingly good in our view. However, the authors showed that the performance across the data sets tested did not improve with model complexity (assessed by number of parameters in the model), a result also found by Asseng et al. (2013) in a comparison of 27 wheat crop simulation models. Independent studies such as that of Asseng et al. (2013) and Soltani and Sinclair (2015) are very valuable and they provide a timely reminder that complexity does not necessarily equate to improved predictive performance. However, the issue is one of designing to be as simple as possible within the intended domain of application and the richness of the data streams to operationalise the model. Take one specific example, APSIM came out as the model with the largest number of "parameters" in Soltani's and Sinclair's (2015) study although users would be expected to set values of around only 10% of these parameters for their crop and soil situation. For example,

one parameter deals with the height of the wheat plant as a function of stem dry weight. The vast majority of wheat simulations would never make use of this parameter – but in a crop-weed or intercrop situations it is fundamental to simulating inter-species light competition in the mixed canopy. Should this parameter be dropped as "unnecessary complexity" for most applications or retained to give the model the generality and flexibility for broader application? The answer probably lies in an examination of the downsides of such additional complexity and parameterisation. If in practice there is little downside and there are important situations where there is an upside, then a mindless pursuit of simplicity seems unhelpful. Einstein went to this place when he suggested "*everything should be as simple as possible – but not simpler*" and Oliver Wendell Holmes Sr explained to us that simplicity per se was not worth "*a fig*" but he would give his life for "*simplicity on the far side of complexity*". These remain important guides to the model builder!

We see a more important issue for the modelling community to address than the complexity–robustness–transparency issue that Soltani and Sinclair (2015) raise. Examination of the rapidly expanding literature making use of such models leaves one with a concern that innovation has stalled over the last decade or so. The literature is starting to have a "sameness" about it – another application of a model in a different country or with a different crop – but are we continuing to see innovation in model building or application? More importantly, are we seeing models being used and making a positive difference in real world situations? In Section 6.2 we highlighted examples of models clearly making positive differences in real world situations. However, of the 280 papers examined for the literature analysis reported above, very few papers showed any evidence that the model use is changing any real decisions for the better, suggesting that the achievements in Section 6.2 are more the exception than the rule. The general lack of evidence that modelling is affecting real decisions comes despite efforts in understanding the processes underpinning delivery of benefits from models (Matthews et al., 2008; Jakku and Thorburn 2010; Hochman and Carberry, 2011; Thorburn et al., 2011; McCown et al., 2012). In terms of model building, innovation in software engineering and design has been integral to innovation in cropping systems modelling. Yet Holzworth et al. (2014b) concluded that there has not been a lot of real innovation obvious in software engineering over the last 10–15 years, achievements have been more a growth in model scope.

As well as there being little evidence of recent innovation in model building or application, many of the key bio-physical routines used in the major models for plant and soil processes have not changed significantly over the last 15–20 years. Does that mean no improvements in the algorithms are possible? Undoubtedly there are still aspects of the current models that can still be improved, such as performance under marginal crop growing conditions (Basso et al., 2016b). But perhaps the benefits of improvements cannot be detected or captured because other factors are dominant in shaping model predictive performance. In the authors' experience, model performance is as much limited by parameterisation data as it is by the inherent validity or specification detail in the model code. High quality data are critical for both the robust development of models, and there is increasing realisation of the value of and need for quality field data (Kersebaum et al., 2015; Porter et al., 2017).

This data issue crosses over into model application as well. The cost effective and timely availability of relevant data has been one of the challenges that has limited model application in real world decision situations. For example, resource use efficiency can be increased by managing fields at finer scales, i.e. through precision agriculture, and modelling has an important role to play in achieving these efficiencies (Basso et al., 2011, 2016a). However, even basic data needed to parameterise models at this scale is usually rare (Wallor et al., 2017). Thus it has been far easier for researchers to conduct scenario analyses in controlled yet theoretical situations where data comes from other times or places or is set up to explore general response functions rather than specific, place based decision problems. We do see prospects for this situation to change in the years ahead through innovations "Internet of Things" (IoT), "cloud computing" and "big data" (Wolfert et al., 2017), and we see this as perhaps the way for the crop modelling community to break out of the "more of the same" rut that we are suggesting it is in or at least approaching. Still, in terms of big data facilitating positive differences in real world situations, there will still be important social complexities that need to be accounted for in applications (Jakku et al., 2016; Wolfert et al., 2017) as we have seen in more "traditional" models applications.

In the world of "big data" and the IoT, we can see the old historical divide between mechanistic crop models and empirical statistical models breaking down. Many applications of crop models are to topics where data are scarce and we have to extrapolate from our current understanding. This need to go beyond the existing data has, in many cases, determined the complexity of the model structure. However, with the prospects for new data streams that are specific to individual farm businesses in close to real time, the possibilities of creative fusion of data with the explanatory and predictive power of well-designed models is exciting. This excitement comes from two drivers. On the one hand, the modellers will have opportunities to innovate in model construction and operation, potentially simplifying models where available data are adequate. Notions of model-data fusion, inverse modelling, new roles for remote and proximal sensing in model initialization and calibration all come into view. Such activities will help to better understand and reduce the uncertainty in model predictions, an important but often overlooked aspect of crop model applications (Wallach and Thorburn, 2017). There may be opportunities to simplify models where data streams provide information (e.g. on soil water) that previously had to be simulated. This "data revolution" goes beyond just input data for models and includes revolutions in related fields such as sensors, robotics, situational awareness for devices, improved climate forecasts and real time weather, proliferation of mobile devices and so on. The un-folding "genomics revolution" also offers hope that genotypic dimensions of crop modelling can be more soundly based on genomics data.

On the other hand, there is a real opportunity to shift the balance in model application towards action research in real world decision making and problem solving settings. These might be the traditional agronomic management issues in farm businesses, operation of plant breeding programs or, for that matter, the design and operation of government policy programs – addressing diverse issues such as nutrient loss and water quality, greenhouse gas emissions and carbon mitigation, etc. The latter application domain places additional requirements on models not found in more conventional applications, such as greater emphasis on quality assurance and control associated with a software "product" (Moore et al., 2015).

The complexity of the application domain for our models continues to evolve. In the 1960′s and 70′s, visionaries such as de Wit, Duncan, Loomis and Nix were focused on crop physiological and agronomic problems whose solutions could be aided by model building and application. Fifty years later, the big issues facing science relate to food and nutritional security, sustainability of the land and water, inclusive development and issues of global change that threaten the planet's future. In fact, our systems science and its application to action research in real world decision making is more important than ever if we are going to make a meaningful contribution to all seventeen Sustainable Development Goals (SDG) (United Nations, 2015) but this does not mean our model scope should continue to expand beyond sensible boundaries that align with science knowledge and application practicality. The art now is to target sound models about components of the global system to generate insights relevant to the wider set of SDG drivers. So the mantra of "models about the world not of the world" remains pertinent. This diverse spectrum of applications all provide opportunity for real engagement with the models – but we need to relentlessly seek to bridge the long standing divide between what Checkland (1981) would call "the world of theory and the world of practice".

Acknowledgments

The senior author's introduction to dynamic crop and soil modelling occurred in 1984 following encouragement from the late RL (Bob) McCown. Over the next 33 years Bob and a great many colleagues in the team around him helped shape modelling insights and experiences. Their inputs are gratefully acknowledged.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.eja.2018.04.007.

References

Arkin, G.F., Taylor, H.M. (Eds.), 1981. Modifying the Root Environment to Reduce Crop Stress. Am. Soc. Agric. Engr., St. Joseph, Michigan (1981) Am. Soc. Agric. Eng. Monogr. No. 4.
Arkin, G.F., Vanderlip, R.L., Ritchie, J.T., 1976. Dynamic grain sorghum growth model. Trans. ASAE 9, 622–630.
Asseng, S., Ewert, F., Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P.J., Rötter, R.P., Cammarano, D., Brisson, N., Basso, B., Martre, P., Aggarwal, P.K., Angulo, C., Bertuzzi, P., Biernath, C., Challinor, A.J., Doltra, J., Gayler, S., Goldberg, R., Grant, R., Heng, L., Hooker, J., Hunt, L.A., Ingwersen, J., Izaurralde, R.C., Kersebaum, K.C., Müller, C., Kumar, S.N., Nendel, C., O'Leary, G., Olesen, J.E., Osborne, T.M., Palosuo, T., Priesack, E., Ripoche, D., Semenov, M.A., Shcherbak, I., Steduto, P., Stöckle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Travasso, M., Waha, K., Wallach, D., White, J.W., Williams, J.R., Wolf, J., 2013. Uncertainty in simulating wheat yields under climate change. Nat. Clim. Change 3, 827–832.
Baker, D.N., Baker, J.R., Lambert, J.M., 1983. GOSSYM: A simulator of cottoncrop growth and yield. S.C. Agric. Exp. Sta. Tech. Bull. 1089, 1–134.
Basso, B., Ritchie, J.T., Cammarano, D., Sartori, L., 2011. A strategic and tactical management approach to select optimal N fertilizer rates for wheat in a spatially variable field. Eur. J. Agron. 35, 215–222.
Basso, B., Dumont, B., Cammarano, D., Pezzuolo, A., Marinello, F., Sartori, L., 2016a. Environmental and economic benefits of variable rate nitrogen fertilization in a nitrate vulnerable zone. Sci. Total Environ. 545–546, 227–235.
Basso, B., Liu, L., Ritchie, J.T., 2016b. A comprehensive review of the CERES-Wheat, –Maize and – Rice models' performances. Adv. Agron. 136, 27–132.
Bassu, S., Brisson, N., Durand, J.L., Boote, K., Lizaso, J., Jones, J.W., Rosenzweig, C., Ruane, A.C., Adam, M., Baron, C., et al., 2014. How do various maize crop models vary in their responses to climate change factors? Global Change Biol. 20, 2301–2320.
Batie, S.S., 2008. Wicked problems and applied economics. Am. J. Agric. Econ. 90, 1176–1191.
Berndt, R.D., White, B.J., 1976. Simulation-based evaluation of three cropping systems on cracking-clay soils in a summer rainfall environment. Agric. Meteorol. 16, 211–299.
Black, C.A., 1967. Soil-Plant Relationships. John Wiley and sons, New York (792 pp).
Blackman, V.H., 1919. The compound interest law and plant growth. Ann. Bot. 33, 353–360.
Boote, K.J., Jones, J.W., Mishoe, J.W., Wilkerson, G.G., 1986. Modeling growth and yield of groundnut. In: Agrometeorology of Groundnut: Proceedings of an International Symposium. Agrometeorology of Groundnut: Proceedings of an International Symposium. 21-26 Aug 1985, ICRISAT Sahelian Center, Niamey, Niger. ICRISAT, Patancheru, A.P., India. pp. 243–254.
Box, G.E.P., 1979. Robustness in the strategy of scientific model building. In: Launer, R.L., Wilkinson, G.N. (Eds.), Robustness in Statistics. Academic Press, pp. 201–236.
Briggs, G.E., 1928. A consideration of some attempts to analyse growth curves. Proc. Roy. Soc. B 102, 280–285.
Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P., Burger, P., Bussie're, F., Cabidoche, Y.-M., Cellier, P., Debaeke, P., Gaudille're, J.-P., Hénault, C., Maraux, F., Seguin, B., Sinoquet, H., 2003. An overview of the crop model STICS. Eur. J. Agron. 18, 309–332.
Brower, R., de Wit, C.T., 1968. In: Whittington, W.J. (Ed.), A Simulation Model of Plant Growth with Special Attention to Root Growth and Its Consequences. Proceedings of the Fifteenth Eastern School in Agricultural Science. University of Nottingham.
Carberry, P.S., Abrecht, D.G., 1991. Tailoring crop models to the semi-arid tropics. In: Muchow, R.C., Bellamy, J.A. (Eds.), Climatic Risk in Crop Production: Models and Management in the Semi-arid Tropics and Subtropics. CAB International, Wallingford, pp. 157–182.
Carberry, P.S., Hochman, Z., McCown, R.L., Dalgliesh, N.P., Foale, M.A., Poulton, P.L., Hargreaves, J.N.G., Hargreaves, D.M.G., Cawthray, S., Hillcoat, N., Robertson, M.J., 2002. The FARMSCAPE approach to decision support: farmers', advisers', researchers' monitoring, simulation, communication and performance evaluation. Agric. Syst. 74, 141–177.
Carberry, P.S., 2005. Increasing the effectiveness of research on agricultural resource management in the semi-arid tropics by combining cropping systems simulation with farming systems research. Adoption of ACIAR Project Outputs: Studies of Projects Completed in 2001–2002. . http://bob-mccown.com/?page_id=17.
Carroll, C., Waters, D., Vardy, S., Silburn, D.M., Attard, S., Thorburn, P.J., Davis, A.M., Schmidt, M., Wilson, B., Clark, A., 2012. A paddock to reef monitoring and modelling framework for the Great Barrier Reef: paddock and catchment component. Mar. Pollut. Bull. 65, 136–149.
Chauhan, Y.S., Wright, G.C., Rachaputi, R.C.N., Holzworth, D., Broome, A., Krosch, S., Robertson, M.J., 2010. Application of a model to assess aflatoxin risk in peanuts. J. Agric. Sci. 148, 341–351.
Checkland, P., 1981. Systems Thinking, Systems Practice. John Wiley, Chichester.
Collinson, M.P., 1982. Farming Systems Research in Eastern Africa: The Experience of CIMMYT and Some National Agricultural Research Services 1976-81, International Agricultural Development Paper No. 3. Michigan State University, East Lansing.
Cooper, M., Technow, F., Messina, C., Gho, G., Totir, L.R., 2016. Use of crop growth models with whole-genome prediction: application to a maize multienvironment trial. Crop Sci. 56, 1–16.
de Wit, C.T., 1953. A Physical Theory on the Placement of Fertilisers. Verst. Landbouwk onderz (Agric Research Report 59) 4. pp. 1–71.
De Willigen, P., Neeteson, J.J., 1985. Comparison of six simulation models for the nitrogen cycle in the soil. Fertil. Res. 8, 157–171.
De Willigen, P., 1991. Nitrogen turnover in the soil-crop system: comparison of fourteen simulation models. Fertil. Res. 27, 141–149.
DeCoursey, D.Q., 1980. Runoff, erosion, and crop yield simulation for land use management. Trans. Am. Soc. Agric. Eng. 23, 379–386.
Dillon, J.L., Virmani, S.M., 1985. The farming systems approach. In: Muchow, R.C. (Ed.), Agro-Research for the Semi-Arid Tropics: North-west Australia. Univ. Queensland Press, St Lucia, pp. 507–532.
Dillon, J.L., 1976. The economics of systems research. Agri. Sys. 1, 5–20.
Dimes, J.P., Revanuru, S., 2004. Evaluation of APSIM to simulate plant growth response to applications of organic and inorganic N and P on an alfisol and vertisol in India. Delve, R.J., Probert, M.E. (Eds.), ACIAR Proceedings No. 114 118–125.
Duncan, W.G., Loomis, R.S., Williams, W.A., Hanau, R., 1967. A model for simulating photosynthesis in plant communities. Hilgardia 38, 181–205.
Duncan, W.G., 1975. Maize. In: Evans, L.T. (Ed.), Crop Physiology – Some Case Histories. Cambridge Uni Press, pp. 374.
Evans, G.C., 1972. The Quantitative Analysis of Plant Growth. Blackwell Scientific Publications, Oxford.
Evans, L.T., 1975. The physiological basis of crop yield. In: Evans, L.T. (Ed.), Crop Physiology – Some Case Histories. Cambridge Uni Press (374 pp).
Fisher, R.A., 1921. Some remarks on the methods formulated in a recent article on the quantitative analysis of plant growth. Ann. Appl. Biol. 7, 367–372.
Fitzpatrick, E.A., Arnold, J.M., 1964. Climate of the west kimberley area. CSIRO Aust. Div. Land Res. Ser. No. 9, 76–102.
Fitzpatrick, E.A., Nix, H.A., 1970. In: Milton Moore, R. (Ed.), The Climatic Factor in Australian Grassland Ecology. Australian Grasslands, ANU Press Canberra, pp. 3–26.
Fitzpatrick, E.A., 1969. Instructions for Preparing Decks for a Computer Program to Carry Out Variable Forms of Weekly Water Balance Accounting. CSIRO Aust. Div. Land Res. Tech. Memo No. 69/7.
Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., et al., 2011. Communicating complexity: integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agric. Syst. 104, 191–203.
Godwin, D.C., Jones, C.A., Ritchie, J.T., Vlek, P.L.G., Youndahl, L.J., 1983. The water and nitrogen components of the CERES Models. In: Proceedings International Symposium on Minimum Data Sets for Agrotechnology Transfer. 21-26 Mar 1983 ICRISAT Patancheru A.P. India,. pp. 101–106.
Gregory, F.G., 1917. Physiological conditions in cucumber houses. 3rd Ann .Rep. Exptl. Res. Stn. Cheshunt 19–28.
Hayman, P., Crean, J., Mullen, J., Parton, K., 2007. How do probabilistic seasonal climate forecasts compare with other innovations that Australian farmers are encouraged to adopt? Aust. J. Agric. Res. 58, 975–984.
Heath, O.V.S., Gregory, F.G., 1938. The constancy of the mean net assimilation rate and its ecological importance. Ann. Bot. ii, 811–$9.
Hochman, Z., Carberry, P.S., 2011. Emerging consensus on desirable characteristics of tools to support farmers' management of climate risk in Australia. Agric. Syst. 104, 441–450.
Hochman, Z., van Rees, H., Carberry, P.S., Hunt, J.R., McCown, R.L., Gartmann, A., Holzworth, D., van Rees, S., Dalgliesh, N.P., Long, W., Peake, A.S., Poulton, P.L., McClelland, T., 2009. Re-inventing model-based decision support with Australian dryland farmers. 4. Yield Prophet® helps farmers monitor and manage crops in a variable climate. Crop Pasture Sci. 60, 1057–1070.
Holzworth, Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., et al., 2014a. APSIM – evolution towards a new generation of agricultural systems simulation. Environ. Modell. Softw. 62, 327–350.
Holzworth, D., Snow, V., Janssen, S., Athanasiadis, I.N., Donatelli, M., Hoogenboom, G., White, J.W., Thorburn, P., 2014b. Agricultural production systems modelling and software: current status and future prospects. Environ. Modell. Softw 62, 327–350.
Hunt, R., 1982. Plant Growth Curves. Edward Arnold, London.
IBSNAT, 1984. Experimental Design and Data Collection Procedures for IBSNAT. The Minimum Data Set for Systems Analysis and Crop Simulation. 1st edition. IBSNAT Technical Report No 1. http://pdf.usaid.gov/pdf_docs/PNABK919. pdf.
Jakku, E., Thorburn, P.J., 2010. A conceptual framework for guiding the participatory development of agricultural decision support systems. Agric. Syst. 103, 675–682.
Jakku, E., Taylor, B., Fleming, A., Mason, C., Thorburn, P., 2016. Big Data, Trust and Collaboration: Exploring the Enabling Socio-technical Conditions of Big Data in the Grains Industry. CSIRO Agriculture and Land and Water Research Report. pp. 34. https://publications.csiro.au/rpr/pub?pid=csiro:EP164134.
Jenkinson, D.S., 1990. The turnover of organic carbon and nitrogen in soil. Philos. Trans. R. Soc. Lond. B 329, 361–368.

Jones, C.A., Kiniry, J.R. (Eds.), 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. Texas A&M University Press, College Station, Texas, pp. 208.
Jones, J.W., Hesketh, J.D., Kamprath, E.J., Bowen, H.D., 1974. Development of a nitrogen balance for cotton growth models: a first approximation. Crop Sci. 14, 541–546.
Jones, C.A., Ritchie, J.T., Kiniry, J.R., Godwin, D.C., Otter, S.I., 1983. The CERES wheat and maize models. In: Proceedings International Symposium on Minimum Data Sets for Agrotechnology Transfer. 21–26 Mar 1983 ICRISAT Patancheru A.P India. pp. 95–100.
Jones, J.W.G., Hoogenboom, C.H., Porter, K.J., Boote, W.D., Batchelor, L.A., Hunt, P.W.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18, 235–265.
Jones, J.W., Antle, J.M., Basso, B.O., Boote, K.J., Conant, R.T., Foster, I., Godfray, H.C.J., Herrero, M., Howitt, R.E., Janssen, S., Keating, B.A., Munoz-Carpena, R., Porter, C.H., Rosenzweig, C., Wheeler, T.R., 2016. Brief history of agricultural system models. Agric. Syst. 155, 240–254.
Keating, B.A., Wafula, B.M., McCown, R.J., 1990. Simulation of plant density effects on maize yields as influenced by water and nitrogen limitations. In: Proc. Internat. Conf. Plant Physiol. New Delhi, Feb. 1988. pp. 547–559.
Keating, B.A., Godwin, D.C., Watiki, J.M., 1991. Optimization of nitrogen inputs under climatic risk. In: Muchow, R.C., Bellamy, J.A. (Eds.), Climatic Risk in Crop Production – Models and Management for the Semi-Arid Tropics and Sub-Tropics. CAB International, Wallingford, UK, pp. 329–357.
Keating, B.A., McCown, R.L., Wafula, B.M., 1992a. Adjustment of nitrogen inputs in response to a seasonal forecast in a region of high climatic risk. In: International Symposium on Systems Approaches to Agricultural Development. Bangkok, Dec 1991., Kluwer Academic publ., Dordrecht, The Netherlands. pp. 233–252.
Keating, B.A., Wafula, B.M., Watiki, J.M., 1992b. Development of a modelling capability for maize in semi-arid eastern Kenya. In: Probert, M.E. (Ed.), A Search for Strategies for Sustainable Dryland Croing in Semi-arid Eastern Kenya. Australian Centre for International Agricultural Research Proceedings No. 41, pp. 26–33.
Keating, B.A., Wafula, B.M., Watiki, J.M., 1992c. Exploring strategies for increased productivity – The case for maize in semi-arid eastern Kenya. In: Probert, M.E. (Ed.), A Search for Strategies for Sustainable Dryland Croing in Semi-arid Eastern Kenya. Australian Centre for International Agricultural Research Proceedings No. 41, pp. 90–100.
Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288.
Keig, G., McAlpine, J.R., 1969. Watbal: A Computer System for the Estimation of Soil Moisture Regimes from Simple Climatic Data. Division of Land Research, Tech Memo 69/9, CSIRO Australia.
Kersebaum, K.C., Hecker, J.-M., Mirschel, W., Wegehenkel, M., et al., 2007. Modelling water and nutrient dynamics in soil–crop systems: a comparison of simulation models alied on common data sets. In: Kersebaum, Kersebaum, K.C. (Eds.), Modelling Water and Nutrient Dynamics in Soil–Crop Systems. Springer, pp. 1–17.
Kersebaum, K.C., Boote, K.J., Jorgenson, J.S., Nendel, C., Bindi, M., Frühauf, C., Gaiser, T., Hoogenboom, G., Kollas, C., Olesen, J.E., Rötter, R.P., Ruget, F., Thorburn, P.J., Trnka, M., Wegehenkel, M., 2015. Analysis and classification of data sets for calibration and validation of agro-ecosystem models. Environ. Modell. Softw 72, 402–417.
Kroon, F., Thorburn, P., Schaffelke, B., Whitten, S., 2016. Towards protecting the Great Barrier Reef from land-based pollution. Global Change Biol. 22, 1985–2002.
Kropff, M.J., Jones, J.W., van Laar, G., 2001. Advances in systems approaches for agricultural development. Agric. Syst. 70, 353–354.
Li, T., Hasegawa, T., Yin, X., Zhu, Y., Boote, K., Adam, M., et al., 2015. Uncertainties in predicting rice yield by current crop models under a wide range of climatic conditions. Glob. Change Biol. 21, 1328–1341.
Littleboy, M., Silburn, D.M., Freebairn, D.M., Woodruff, D.R., Hammer, G.L., Leslie, J.K., 1992. Impact of soil erosion on production in cropping systems. I. Development and validation of a simulation model. Aust. J. Soil Res. 30, 757–774.
Loomis, R.S., Williams, W.A., Hall, A.E., 1971. Agricultural productivity. Annu. Rev. Plant. Physiol. 22, 431–468.
Manzoni, S., Porporato, A., 2009. Soil carbon and nitrogen mineralization: theory and models across scales. Soil Biol. Biochem. 41, 1355–1379.
Marin, F.R., Thorburn, P.J., Nassif, D.S.P., Costa, L.G., 2015. Sugarcane model intercomparison: structural differences and uncertainties under climate change. Environ. Modell. Softw. 72, 372–386.
Matthews, R., Stephens, W. (Eds.), 2002. Crop-soil Simulation Models: Applications in Developing Countries. CAB International, Wallingford UK, pp. 227.
Matthews, R.B., Stephens, W., Hess, T., Middleton, T., Graves, A.R., 2002. Application of crop/soil simulation models in tropical agricultural systems. Adv. Agron. 76, 31–124.
Matthews, K., Schwarz, G., Buchan, K., Rivington, M., Miller, D., 2008. Wither agricultural DSS? Comput. Electron. Agric. 61, 149–159.
Matthews, K.B., Rivington, M., Blackstock, K., McCrum, G., Buchan, K., Miller, D.G., 2011. Raising the bar? – The challenges of evaluating the outcomes of environmental modelling and software. Environ. Modell. Softw. 26, 247–257.
McAlpine, J.R., 1970. Estimating pasture growth periods and droughts from simple water balance models. Proc. 11th International Grassland Congress.
McCown, R.L., Keating, B.A., 1992. Looking forward: finding a path for sustainable development. In: Probert, M.E. (Ed.), A Search for Strategies for Sustainable Dryland Croing in Semi-arid Eastern Kenya. Australian Centre for International Agricultural Research Proceedings No. 41, pp. 126–132.
McCown, R.L., Keating, B.A., Probert, M.E., Jones, R.K., 1992. Strategies for sustainable crop production in semi-arid Africa. Outlook Agric. 21, 21–31.
McCown, R.L., Cox, P.G., Keating, B.A., Hammer, G.L., Carberry, P.S., Probert, M.E., Freebairn, D.M., 1994. The development of strategies for improved agricultural systems and land use management. In: Goldsworthy, P., Penning de Vries, F. (Eds.), Opportunities, Use, and Transfer of Systems Research Methods in Agriculture to Developing Countries. Kluwer Academic publ., Dordrecht, The Netherlands, pp. 81–96.
McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P., Freebairn, D.M., 1996. APSIM: a novel software system for model development, model testing, and simulation in agricultural systems research. Agric. Syst. 50, 255–271.
McCown, R.L., Keating, B.A., Carberry, P.C., Hochman, Z.H., Hargreaves, D., 2002. The co-evolution of the Agricultural Production Systems Simulator (APSIM) and its use in Australian dryland cropping research and intervention. In: Ahuja, L.R., Ma, L., Howell, T.A. (Eds.), Agricultural Systems Models in Field Research and Technology Transfer. CRC Press, Boca Raton, Florida, USA.
McCown, R.L., Carberry, P.S., Dalgliesh, N.P., Foale, M.A., Hochman, Z., 2012. Farmers use intuition to reinvent analytic decision support for managing seasonal climatic variability. Agric. Syst. 106, 33–45.
McCown, R., 2002. Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. Agric. Syst. 74, 179–220.
Messina, C.D., Technow, F., Tang, T., Totir, R., Gho, C., Cooper, M., 2018. Leveraging biological insight and environmental variation to improve phenotypic prediction: integrating crop growth models (CGM) with whole genome prediction (WGP). Eur. J. Agron (this issue).
Monsi, M., Saeki, T., 1953. Über den Lichtfaktor in den Pflanzengesellschaften und seine Bedeutung für die Stoffproduktion. Jpn. J. Bot. 14, 22–52.
Moore, A.D., Eckard, R.J., Thorburn, P.J., Grace, P.R., Wang, E., Chen, D., 2015. Mathematical modelling for improved greenhouse gas balances: agro-ecosystems and policy development: lessons from the Australian experience. WIREs Clim. Change 5, 735–752.
Morgan, J.M., 1976. A Simulation Model of the Growth of the Wheat Plant. Macquarie Univ., Australia, pp. 192 (Ph.D. Thesis 192 pp).
Muchow, R.C., Bellamy, J.A., 1991. Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics. CAB Wallingford, UK (548 pp).
Nix, H., 1983. Minimum datasets for agro-technology transfer. In: Proceedings International Symposium on Minimum Data Sets for Agrotechnology Transfer. 21–26 Mar 1983 ICRISAT Patancheru A.P., India. pp. 101–108.
Nix, H., 1985. Improving research efficiency. In: Muchow, R.C. (Ed.), Agro-Research for the Semi-Arid Tropics: North-west Australia. Univ. Queensland Press, St Lucia.
Oquist, P., 1978. The epistemology of action research. Acta Sociol. 21, 43–163.
Passioura, J.B., 1996. Simulation models: science; snake oil, education, or engineering? Agron. J. 88, 690–694.
Penning de Vries, F., Teng, P., Metselaar, K., 1993. Proceedings of the International Symposium on Systems Approaches for Agricultural Development, 2–6 December 1991, Bangkok Thailand. Springer, Netherlands, pp. 542.
Poorter, H., Gamier, E., 1996. Plant growth analysis: an evaluation of experimental design and computational methods. J. Exp. Bot. 47, 1343–1351.
Porter, J.R., Howden, M., Smith, P., 2017. Considering agriculture in IPCC assessments. Nat. Clim. Change 7, 680–683.
Powlson, D., Smith, P., Nobili, M.D., 2013. Soil organic matter. In: Gregory, P.J., Nortcliff, S. (Eds.), Soil Conditions and Plant Growth. Blackwell Publishing Ltd, Oxford, pp. 86–131.
Probert, M.E., Keating, B.A., Thompson, J.P., Parton, W.J., 1995. Modelling water, nitrogen and crop yield for a long-term fallow management experiment. Austr. J. Exp. Agric. 35, 941–950.
Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8, 1204–1213.
Ritchie, J.T., 1973. Influence of soil water status and meteorological conditions on evaporation from a corn canopy. Agron. J. 65, 893–897.
Robertson, M.J., Rebetzke, G.J., Norton, R.M., 2015. Assessing the place and role of crop simulation modelling in Australia. Crop Pasture Sci. 66, 877–893.
Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P., Antle, J.M., Nelson, G.C., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorria, G., Winter, J.M., 2013. The agricultural model intercomparison and improvement project (AgMIP): protocols and pilot studies. Agric. For. Met. 170, 166–182.
Rotter, R.P., Ewert, F., Palosuo, T., Bindi, M., Kersebaum, K.C., Olesen, J.E., Trnka, M., van Ittersum, M.K., Janssen, S., Rivington, M., Semenov, M., Wallach, D., Porter, J.R., Stewart, D., Verhagen, J., Angulo, C., Gaiser, T., Nendel, C., Martre, P., de Wit, A., 2013. Challenges for agro-ecosystem modelling in climate change risk assessment for major European crops and farming systems. In: Impacts World 2013 Conference Proceedings. Potsdam Institute for Climate Impact Research, Potsdam. pp. 555–564.
Russell, E.J., 1912. Soil Conditions and Plant Growth, 1st edition. Longmans, London.
Seligman, N.G., Van Keulen, H., 1981. PAPRAN: a simulation model of annual pasture production limited by rainfall and nitrogen. In: Frissel, M.J., Van Veen, J.A. (Eds.), Simulation of Nitrogen Behaviour of Soil-Plant Systems. Pudoc, Wageningen, The Netherlands, pp. 192–220.
Shaffer, M.J., Gupta, S.C., Linden, D.R., Molina, J.A.E., Clapp, C.E., Larson, W., 1982. Simulation of nitrogen, tillage, and residue management effects on soil fertility. Analysis of Ecological Systems: state-of the- Art in Ecological Modeling. In: Skogerboe, M. (Ed.), Proc. 3rd. Int, Conf. On State-of-the-Art in Ecological Modeling. Colorado State University Boulder, CO, May 24–28. pp. 525–543.
Shaner, W.W., Philipp, P.E., Schmehl, W.R., 1981. Farming Systems Research and Development: Guidelines for Developing Countries. Westview Press Boulder, Colorado.
Sierra, C.A., Mulller, M., Trumbore, S.E., 2012. Models of soil organic matter decomposition: the SoilR package, version 1.0. Geosci. Model Dev. 5, 1045–1060.

Silva, J.A., Uehara, G., 1985. Transfer of agrotechnology. Ch. 1. In: Silva, J.A. (Ed.), Soil-based Agrotechnology Transfer. Benchmark Soils Project. Dept. Agronomy and Soil Science, Hawaii Institute of Tropical Agriculture, Uni of Hawaii 292 pp.
Slatyer, R.O., 1959. Internal water balance of Acacia aneura f. Muell. in relation to environmental conditions. In: Symposium on Plant-Water Relationships in Arid and Semi-arid Conditions. Madrid, 1959. pp. 8 (NS/AZ/453, WS/079.151).
Slatyer, R.O., 1960. Agricultural Climatology of the Yass Valley. CSIRO Aust. Div. Land Res. Reg. Surv. Tech. Paper Nos. 6 and 13.
Slatyer, R.O., 1964. Climate of the Leichhardt-Gilbert Area. CSIRO Aust. Land Res. Ser. No. 11.
Slatyer, R.O., 1965. The Use of soil water balance relationships in agroclimatology. Symposium on Methods in Agroclimatology. Reading, UK (1966, 39 pp).
Smith, P., Smith, J.U., Powlsen, D.S., McGill, W.B., Arah, J.R.M., Chertov, O.G., Coleman, K., Franko, U., Frolking, S., Jenkinson, D.S., Jensen, L.S., Kelly, R.H., Klein-Gunnewiek, H., Komarov, A.S., Li, C., Molina, J.A.E., Mueller, T., Parton, W.J., Thornley, J.H.M., Whitmore, A.P., 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81, 153–225.
Soltani, A., Sinclair, T.R., 2015. A comparison of four wheat models with respect to robustness and transparency: simulation in a temperate, sub-humid environment. Field Crops Res. 175, 37–46.
Sorensen, J.T., Kristensen, E.S., 1992. Systemic modelling: a research methodology in livestock farming. In: Gibon, A., Matheron, B. (Eds.), Global Appraisal of Livestock Farming Systems and Study on Their Organizational Levels: Concept, Methodology and Results, Proc. Symp Organized by INRA-SAD and the DIRAD-IEMVT. Toulouse, France, July 7–10, 1990. pp. 45–57 (Commission of European Communities).
Stöckle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agron. 18, 289–307.
Steiner, J.L., Williams, J.R., Jones 0, R., 1987. Evaluation of the EPIC simulation model using a dryland wheat-sorghum-fallow crop rotation. Agron. J. 79, 732–738.
Sterk, B., Carberry, P., Leeuwis, C., Van Ittersum, M.K., Howden, M., Meinke, H., Van Keulen, H., Rossing, W.A.H., 2009. The interface between land use systems research and policy: multiple arrangements and leverages. Land Use Policy 26, 434–442.
Stinson, D.L., Arkin, G.F., Howell, T.A., Richardson, C.W., Williams, J.R., 1981. Modeling grain sorghum ratoon cropping and associated runoff and sediment losses. Trans. ASAE-1981 631–642.
Stroosnijder, L., van Keulen, H., Vachaud, G., 1972. Water movement in layered soils. 2. Experimental confirmation of a simulation model. Neth. J. Agric Sci. 20, 67–72.
Technow, F., Messina, C.D., Totir, L.R., Cooper, M., 2015. Integrating crop growth models with whole genome prediction through approximate Bayesian computation. PLoS One 10 (6), e0130855.
Teng, P., Kropff, M.J., ten Berge, H.F.M., Dent, J.B., Lansigan, F.P., Van Laar, et al., 1997. Applications of systems approaches at the farm and regional levels. In: Proceedings of the Second International Symposium on Systems Approaches for Agricultural Development, Held at IRRI. Los Banos, Philippines, 6–8 December 1995. Springer Dordrecht.
Thorburn, P.J., Jakku, E., Webster, A.J., Everingham, Y.L., 2011. Agricultural decision support systems facilitating co-learning: a case study on environmental impacts of sugarcane production. Int. J. Agric. Sustain. 9, 322–333.
Thornley, J.H.M., 1976. Mathematical Models in Plant Physiology: A Quantitative Approach to Problems in Plant and Crop Physiology. Academic Press, 1976 London, New York (318 pp).
United Nations, 2015. General Assembly Resolution 70/1, Transforming Our World: The 2030 Agenda for Sustainable Development, A/RES/70/1 (15 September 2015). https://sustainabledevelopment.un.org/post2015/transformingourworld/publication.
van Bavel, C.H.M., 1953. A drought criterion and its application in evaluating drought incidence and hazard. J. Agron. 4, 167–172.
van Ittersum, M.K., Leffelaar, P.A., van Keulen, H., Kropff, M.J., Bastiaans, L., Goudriaan, J., 2003. On approaches and applications of the Wageningen crop models. Eur. J. Agron. 18, 289–307.
van Ittersum, M.K., Ewert, F., Heckelei, T., Wery, J., Alkan Olsson, J., Andersen, E., Bezlepkina, I., Brouwer, F., Donatelli, M., Flichman, G., Olsson, L., Rizzoli, A.E., van der Wal, T., Wien, J.E., Wolf, J., 2008. Integrated assessment of agricultural systems—a component-based framework for the European Union (SEAMLESS). Agric. Syst. 96, 150–165.
van Keulen, H., van Beek, C.G.E.M., 1971. Water movement in layered soils – a simulation model. Neth. J. Agric. Sci. 19, 138–153.
van Keulen, H., 1977. Nitrogen Requirements of Rice with Special Reference to Java. Contributions Central Research Institute for Agriculture, Bogor Indonesia, pp. 67 (No 30).
van Rees, H., McClelland, T., Hochman, Z., Carberry, P., Hunt, J., Huth, N., Holzworth, D., 2014. Leading farmers in South East Australia have closed the exploitable wheat yield gap: prospects for further improvement. Field Crops Res. 164, 1–11.
Venus, J.C., Causton, D.R., 1979. Plant growth analysis: the use of the Richards function as an alternative to polynomial exponentials. Ann. Bot. 43, 623–632.
Wallach, D., Thorburn, P.J., 2017. Estimating uncertainty in crop model predictions: current situation and future prospects. Eur. J. Agron. 88, A1–A7.
Wallor, E., KersebaumK, C., Lorenz, K., Gebbers, R., 2017. Connecting crop models with highly resolved sensorobservations to improve site-specific fertilization. Adv. Animal Biosci.: Precision Agric. (ECPA) 8 (2), 689–693.
Watson, D.J., 1947. Comparative physiological studies on the growth of field crops: I: variation in net assimilation rate and leaf area between species and varieties and within and between years. Ann. Bot. 11, 41–76.
West, C., Briggs, G.E., Kidd, F., 1920. Methods and significant relations in the quantitative analysis of plant growth. New Phytol. 19, 200–207.
Whitbread, A.M., Robertson, M.J., Carberry, P.S., Dimes, J.P., 2010. How farming systems simulation can aid the development of more sustainable smallholder farming systems in southern Africa. Eur. J. Agron. 32, 51–58.
Wilkerson, G.G., Jones, J.W., Boote, K.J., Ingram, K.T., Mishoe, J.W., 1983. Modeling soybean growth for crop management. Trans. ASAE 26, 63–73.
Williams, J., Jones, C.A., Kiniry, J.R., Spanel, D.A., 1989. The EPIC crop growth model. Trans. ASAE 32, 497–511.
Williams, R.F., 1946. The physiology of plant growth with special reference to the concept of net assimilation rate. Ann. Bot. 10, 41–72.
Williams, J.R., 1978. Runoff simulation model. In: Presented at the SCS/SEA Hydrology Workshop. Brainerd, MN. August 21–25, 1978.
Wolfert, S., Ge, L., Verdouw, C., Bogaardt, M., 2017. Big data in smart farming – a review. Agric. Syst. 153, 69–80.
Yin, X., Goudriaan, J., Lantinga, E.A., Vos, J., Spiertz, H.J., 2003. A flexible sigmoid function of determinate growth. Ann. Bot. 91, 1–11.